ELECTRONICALLY TUNABLE COMBLINE FILTERS TUNED BY TUNABLE DIELECTRIC CAPACITORS

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of United States Provisional Application No. 60/227,438, filed August 22, 2000.

FIELD OF INVENTION

The present invention generally relates to electronic filters, and more particularly, to tunable filters.

BACKGROUND OF INVENTION

Electrically tunable filters have many uses in microwave and radio frequency systems. Compared to mechanically and magnetically tunable filters, electronically tunable filters have the important advantage of fast tuning capability over wide band application. Because of this advantage, they can be used in the applications such as LMDS (local multipoint distribution service), PCS (personal communication system), frequency hopping, satellite communication, and radar systems.

One electronically tunable filter is the diode varactor-tuned filter. Since a diode varactor is basically a semiconductor diode, diode varactor-tuned filters can be used in monolithic microwave integrated circuits (MMIC) or microwave integrated circuits. The performance of varactors is defined by the capacitance ratio, C_{max}/C_{min}, frequency range, and figure of merit, or Q factor at the specified frequency range. The Q factors for semiconductor varactors for frequencies up to 2 GHz are usually very good. However, at frequencies above 2 GHz, the Q factors of these varactors degrade rapidly.

Since the Q factor of semiconductor diode varactors is low at high frequencies (for example, < 20 at 20 GHz), the insertion loss of diode varactor-tuned filters is very high, especially at high frequencies (> 5 GHz). Another problem associated with diode varactor-tuned filters is their low power handling capability. Since diode varactors are nonlinear devices, larger signals generate harmonics and subharmonics.

Varactors that utilize a thin film ferroelectric ceramic as a voltage tunable element in combination with a superconducting element have been described. For example, United States Patent No. 5,640,042 discloses a thin film ferroelectric varactor having a carrier

substrate layer, a high temperature superconducting layer deposited on the substrate, a thin film dielectric deposited on the metallic layer, and a plurality of metallic conductive means disposed on the thin film dielectric, which are placed in electrical contact with RF transmission lines in tuning devices. Another tunable capacitor using a ferroelectric element in combination with a superconducting element is disclosed in United States Patent No. 5,721,194.

Commonly owned United States Patent Application Serial No. 09/419,219, filed October 15, 1999, and titled "Voltage Tunable Varactors And Tunable Devices Including Such Varactors", discloses voltage tunable dielectric varactors that operate at room temperature and various devices that include such varactors, and is hereby incorporated by reference.

Combline filters, using resonant cavities, are attractive for use in electronic devices because of their merits such as smaller size, wider spurious free performance compared to the standard waveguide based cavity filters.

There is a need for tunable filters that can operate at radio and microwave frequencies with reduced intermodulation products and at temperatures above those necessary for superconduction.

SUMMARY OF THE INVENTION

Voltage-controlled tunable filters constructed in accordance with this invention include first and second cavity resonators, means for exchanging a signal between the first and second resonators, a first voltage tunable dielectric capacitor positioned within the first resonator, means for applying a control voltage to the first voltage tunable dielectric capacitor, a second voltage tunable dielectric capacitor positioned within the second resonator, means for applying a control voltage to the second voltage tunable dielectric capacitor, an input coupled to the first coaxial resonator, and an output coupled to the first coaxial resonator.

In a first embodiment of the invention, each of the first and second voltage tunable dielectric capacitors includes a first electrode, a tunable dielectric film positioned on the first electrode, and a second electrode positioned on a surface of the tunable dielectric film opposite the first electrode.

In another embodiment, each of the first and second voltage tunable dielectric capacitors includes a substrate, a tunable dielectric film positioned on the substrate, and an

electrode positioned on a surface of the tunable dielectric film opposite the substrate. The electrode can be divided into first and second electrodes, separated to form a gap.

An insulating material can be included for insulating the first and second electrodes from the resonator. The tunable dielectric film can comprise barium strontium titanate or a composite of barium strontium titanate.

The voltage-controlled tunable filter can further comprise a first rod positioned in the first resonator, wherein the first voltage tunable dielectric capacitor is positioned at one end of the first rod, and a second rod positioned in the second resonator, wherein the second voltage tunable dielectric capacitor is positioned at one end of the second rod. Each of the rods in the coaxial resonators can be serially connected with one of the voltage tunable dielectric capacitors, and a second end of each of the rods can be connected to ground.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a top plan view of a voltage controlled tunable dielectric capacitor that can be used in the filters of this invention;

Figure 2 is a cross sectional view of the capacitor of Figure 1 taken along line 2-2;

Figure 3 is a top plan view of another voltage controlled tunable dielectric capacitor that can be used in the filters of this invention;

Figure 4 is a cross sectional view of the capacitor of Figure 3 taken along line 4-4;

Figure 5 is a graph of the capacitance versus voltage of a voltage controlled tunable dielectric capacitor that can be used in the filters of this invention;

Figure 6 is a pictorial representation of a filter constructed in accordance with this invention;

Figure 7 is a pictorial representation of another filter constructed in accordance with this invention;

Figure 8 is a graph of the frequency response of an electronically tunable combline filter constructed in accordance with this invention, with the unloaded Q of 300 under zero bias; and

Figure 9 is a graph of the frequency response of an electronically tunable combline filter constructed in accordance with this invention, with the unloaded Q of 250 under full bias.

DETAILED DESCRIPTION OF THE INVENTION

Referring to the drawings, Figure 1 is a top plan view of a voltage controlled tunable dielectric capacitor 10 that can be used in the filters of this invention. Figure 2 is a cross sectional view of the capacitor 10 of Figure 1 taken along line 2-2. The capacitor includes a first electrode 12, a layer, or film, of tunable dielectric material 14 positioned on a surface 16 of the first electrode, and a second electrode 18 positioned on a side of the tunable dielectric material 14 opposite from the first electrode. The first and second electrodes are preferably metal films or plates. An external voltage source 20 is used to apply a tuning voltage to the electrodes, via lines 22 and 24. This subjects the tunable material between the first and second electrodes to an electric field. This electric field is used to control the dielectric constant of the tunable dielectric material. Thus the capacitance of the tunable dielectric capacitor can be changed.

Figure 3 is a top plan view of another voltage controlled tunable dielectric capacitor 26 that can be used in the filters of this invention. Figure 4 is a cross sectional view of the capacitor of Figure 3 taken along line 4-4. The tunable dielectric capacitor of Figures 3 and 4 includes a top conductive plate 28, a low loss insulating material 30, a bias metal film 32 forming two electrodes 34 and 36 separated by a gap 38, a layer of tunable material 40, a low loss substrate 42, and a bottom conductive plate 44. The substrate 42 can be, for example, MgO, $LaAlO_3$, alumina, sapphire or other materials. The insulating material can be, for example, silicon oxide or a benzocyclobutene-based polymer dielectrics. An external voltage source 46 is used to apply voltage to the tunable material between the first and second electrodes to control the dielectric constant of the tunable material.

The tunable dielectric film of the capacitors shown in Figures 1a and 2a, is typical Barium-strontium titanate, $Ba_xSr_{1-x}TiO_3$ (BSTO) where $0 < x < 1$, BSTO-oxide composite, or other voltage tunable materials. Between electrodes 34 and 36, the gap 38 has a width g, known as the gap distance. This distance g must be optimized to have higher C_{max}/C_{min} in order to reduce bias voltage, and increase the Q of the tunable dielectric capacitor. The typical g value is about 10 to 30 μm. The thickness of the tunable dielectric layer affects the ratio C_{max}/C_{min} and Q. For tunable dielectric capacitors, parameters of the structure can be chosen to have a desired trade off among Q, capacitance ratio, and zero bias capacitance of the tunable dielectric capacitor. It should be noted that other key effect on the property of the tunable dielectric capacitor is the tunable dielectric film. The typical Q factor

of the tunable dielectric capacitor is about 200 to 500 at 1 GHz, and 50 to 100 at 20 to 30 GHz. The C_{max}/C_{min} ratio is about 2, which is independent of frequency. A typical variation in capacitance with applied voltage of the tunable dielectric capacitor at 2 GHz with a gap of 20 μm at a temperature of 300° K, is shown in Figure 5.

Figure 6 is a pictorial representation of a filter 50 constructed in accordance with this invention. The filter includes a plurality of cylindrical coaxial cavity resonators 52, 54, 56 and 58. A rod 60 is positioned along the axis of resonator 52. Additional rods 62, 64 and 66 are positioned along the axes of resonators 54, 56 and 58. A voltage tunable capacitor, as illustrated in Figures 1 and 2 or 3 and 4, is positioned adjacent to one end of each of the rods. The resonators are electrically coupled in series with each other using, for example, channels 68 and 70 connected between openings 72, 74 and 76, 78 in the walls 80, 82, 84 and 86 of the resonators. An input 88, in the form of a probe, is connected to resonator 52. An output 90, in the form of a probe, is connected to resonator 58. One or more external voltage sources, for example 92 and 94, are connected to the tunable capacitors 10 at the ends of the rods to control the capacitance of the tunable capacitors. The rods, and the entire cavity resonator, can be made of metal, but other materials such as plastic, provided they are plated with good conductor, could be used. The tunable capacitors can be positioned anywhere in the vicinity of the rod, as long as they perturb the electromagnetic fields surrounding it.

Figure 7 is a pictorial representation of another filter 100 constructed in accordance with this invention. The filter includes a plurality of rectangular cavity resonators 102, 104, 106 and 108. A rod 110 is positioned along the axis of resonator 102. Additional rods 112, 114 and 116 are positioned along the axes of resonators 104, 106 and 108. A voltage tunable capacitor, as illustrated in Figures 1 and 2 or 3 and 4, is positioned adjacent to one end of each of the rods. The resonators are electrically coupled in series with each other using, for example, channels 118 and 120 connected between openings 122, 124 and 126, 128 in the walls 130, 132, 134 and 136 of the resonators. An input 138, in the form of a probe, is connected to resonator 102. An output 140, in the form of a probe, is connected to resonator 108. One or more external voltage sources, for example 142 and 144, would be connected to the tunable capacitors at the ends of the rods to control the capacitance of the capacitors.

General configurations of electronically tunable microwave coaxial combline filters tuned by the tunable dielectric capacitor are shown in Figures 6 and 7. Figure 6 shows the cylindrical coaxial combline resonator based electronically tunable filter. Figure 7 shows

the rectangular coaxial combline resonator based electronically tunable filter. Computer simulated performance characteristics for the filters of Figures 6 and 7 are presented in Figures 8 and 9. By employing the presented filter topologies, for example, a 4-pole filter with the bandwidth 50MHz at 2.2 GHz can be tuned from the initial state (zero bias) centered at 2.0 GHz to the final state (full bias) centered at 2.4 GHz with the assumption that the tunable dielectric capacitor have a capacitance ratio of 2.

Figure 8 shows a computer-simulated frequency response of the tunable filter with zero-biased tunable dielectric capacitors. The capacitance of the tunable dielectric capacitors was assumed to be 1.0 pF at zero bias. The center frequency of the filter is 2GHz, and the equal ripple bandwidth is 50 MHz. Figure 9 is a simulated frequency response of the tunable filter under the full bias, where the capacitance of the tunable dielectric capacitor was assumed to be 0.5pF. The center frequency of the filter can be tuned up to 2.4 GHz. The bandwidth of the filter under full bias voltage can be kept unchanged compared to that under zero bias. For the filter in Figure 6, it is assumed that total unloaded Q of the combline resonators plus the tuning element is equal to 300, which is equivalent to 2.8 dB losses. For the filter in Figure 7, it is assumed that total unloaded Q of combline resonators plus the tuning element is equal to 250, which corresponds to 4.0 dB insertion loss. The loss of the filter based on the three-dimensional structures is smaller than that based on the planar structure with similar characteristics.

The filters of the present invention have low insertion loss, fast tuning speed, high power-handling capability, high IP3 and low cost in the microwave frequency range. Compared to the voltage-controlled semiconductor varactors, voltage-controlled tunable dielectric capacitors have higher Q factors, higher power-handling and higher IP3. Voltage-controlled tunable dielectric capacitors have a capacitance that varies approximately linearly with applied voltage and can achieve a wider range of capacitance values than is possible with semiconductor diode varactors.

The tunable dielectric capacitor in the preferred embodiment of the present invention can include a low loss $(Ba,Sr)TiO_3$-based composite film. The typical Q factor of the tunable dielectric capacitors is 200 to 500 at 2 GHz with capacitance ratio (C_{max}/C_{min}) around 2. A wide range of capacitance of the tunable dielectric capacitors is variable, say 0.1 pF to 10 pF. The tuning speed of the tunable dielectric capacitor is less than 30 ns. The practical tuning speed is determined by auxiliary bias circuits. The tunable dielectric capacitor is a packaged two-port component, in which tunable dielectric can be voltage-

controlled. The tunable film is deposited on a substrate, such as MgO, $LaAlO_3$, sapphire, Al_2O_3 and other dielectric substrates. An applied voltage produces an electric field across the tunable dielectric, which produces an overall change in the capacitance of the tunable dielectric capacitor.

The tunable filter in the present invention is a coaxial resonator based combline tunable filter. The resonator is a metallic cavity loaded with an inner rod. The one end of the rod is grounded and the other end is serially connected with a grounded tuning capacitor. Variation of the capacitance of the tunable capacitor affects the electrical length of the coaxial combline resonator, which varies the resonant frequency of the coaxial combline resonator. The openings on the sides of the cavities are used to provide the necessary couplings between the coaxial combline resonators.

Accordingly, the present invention, by utilizing the unique application of high Q tunable dielectric capacitors, provides a high performance microwave electronically tunable filter.

Tunable dielectric materials have been described in several patents. Barium strontium titanate ($BaTiO_3$ - $SrTiO_3$), also referred to as BSTO, is used for its high dielectric constant (200-6,000) and large change in dielectric constant with applied voltage (25-75 percent with a field of 2 Volts/micron). Tunable dielectric materials including barium strontium titanate are disclosed in U.S. Patent No. 5,427,988 by Sengupta, et al. entitled "Ceramic Ferroelectric Composite Material-BSTO-MgO"; U.S. Patent No. 5,635,434 by Sengupta, et al. entitled "Ceramic Ferroelectric Composite Material-BSTO-Magnesium Based Compound"; U.S. Patent No. 5,830,591 by Sengupta, et al. entitled "Multilayered Ferroelectric Composite Waveguides"; U.S. Patent No. 5,846,893 by Sengupta, et al. entitled "Thin Film Ferroelectric Composites and Method of Making"; U.S. Patent No. 5,766,697 by Sengupta, et al. entitled "Method of Making Thin Film Composites"; U.S. Patent No. 5,693,429 by Sengupta, et al. entitled "Electronically Graded Multilayer Ferroelectric Composites"; U.S. Patent No. 5,635,433 by Sengupta entitled "Ceramic Ferroelectric Composite Material BSTO-ZnO"; U.S. Patent No. 6,074,971 by Chiu et al. entitled "Ceramic Ferroelectric Composite Materials with Enhanced Electronic Properties BSTO-Mg Based Compound-Rare Earth Oxide". These patents are incorporated herein by reference.

Barium strontium titanate of the formula $Ba_xSr_{1-x}TiO_3$ is a preferred electronically tunable dielectric material due to its favorable tuning characteristics, low Curie temperatures and low microwave loss properties. In the formula $Ba_xSr_{1-x}TiO_3$, x can be any

value from 0 to 1, preferably from about 0.15 to about 0.6. More preferably, x is from 0.3 to 0.6.

Other electronically tunable dielectric materials may be used partially or entirely in place of barium strontium titanate. An example is $Ba_xCa_{1-x}TiO_3$, where x is in a range from about 0.2 to about 0.8, preferably from about 0.4 to about 0.6. Additional electronically tunable ferroelectrics include $Pb_xZr_{1-x}TiO_3$ (PZT) where x ranges from about 0.0 to about 1.0, $Pb_xZr_{1-x}SrTiO_3$ where x ranges from about 0.05 to about 0.4, $KTa_xNb_{1-x}O_3$ where x ranges from about 0.0 to about 1.0, lead lanthanum zirconium titanate (PLZT), $PbTiO_3$, $BaCaZrTiO_3$, $NaNO_3$, $KNbO_3$, $LiNbO_3$, $LiTaO_3$, $PbNb_2O_6$, $PbTa_2O_6$, $KSr(NbO_3)$ and $NaBa_2(NbO_3)_5KH_2PO_4$, and mixtures and compositions thereof. Also, these materials can be combined with low loss dielectric materials, such as magnesium oxide (MgO), aluminum oxide (Al_2O_3), and zirconium oxide (ZrO_2), and/or with additional doping elements, such as manganese (MN), iron (Fe), and tungsten (W), or with other alkali earth metal oxides (i.e. calcium oxide, etc.), transition metal oxides, silicates, niobates, tantalates, aluminates, zirconnates, and titanates to further reduce the dielectric loss.

In addition, the following U.S. Patent Applications, assigned to the assignee of this application, disclose additional examples of tunable dielectric materials: U.S. Application Serial No. 09/594,837 filed June 15, 2000, entitled "Electronically Tunable Ceramic Materials Including Tunable Dielectric and Metal Silicate Phases"; U.S. Application Serial No. 09/768,690 filed January 24, 2001, entitled "Electronically Tunable, Low-Loss Ceramic Materials Including a Tunable Dielectric Phase and Multiple Metal Oxide Phases"; U.S. Application Serial No. 09/882,605 filed June 15, 2001, entitled "Electronically Tunable Dielectric Composite Thick Films And Methods Of Making Same"; U.S. Application Serial No. 09/834,327 filed April 13, 2001, entitled "Strain-Relieved Tunable Dielectric Thin Films"; and U.S. Provisional Application Serial No. 60/295,046 filed June 1, 2001 entitled "Tunable Dielectric Compositions Including Low Loss Glass Frits". These patent applications are incorporated herein by reference.

The tunable dielectric materials can also be combined with one or more non-tunable dielectric materials. The non-tunable phase(s) may include MgO, $MgAl_2O_4$, $MgTiO_3$, Mg_2SiO_4, $CaSiO_3$, $MgSrZrTiO_6$, $CaTiO_3$, Al_2O_3, SiO_2 and/or other metal silicates such as $BaSiO_3$ and $SrSiO_3$. The non-tunable dielectric phases may be any combination of the above, e.g., MgO combined with $MgTiO_3$, MgO combined with $MgSrZrTiO_6$, MgO

combined with Mg_2SiO_4, MgO combined with Mg_2SiO_4, Mg_2SiO_4 combined with $CaTiO_3$ and the like.

Additional minor additives in amounts of from about 0.1 to about 5 weight percent can be added to the composites to additionally improve the electronic properties of the films. These minor additives include oxides such as zirconnates, tannates, rare earths, niobates and tantalates. For example, the minor additives may include $CaZrO_3$, $BaZrO_3$, $SrZrO_3$, $BaSnO_3$, $CaSnO_3$, $MgSnO_3$, $Bi_2O_3/2SnO_2$, Nd_2O_3, Pr_7O_{11}, Yb_2O_3, Ho_2O_3, La_2O_3, $MgNb_2O_6$, $SrNb_2O_6$, $BaNb_2O_6$, $MgTa_2O_6$, $BaTa_2O_6$ and Ta_2O_3.

Thick films of tunable dielectric composites can comprise $Ba_{1-x}Sr_xTiO_3$, where x is from 0.3 to 0.7 in combination with at least one non-tunable dielectric phase selected from MgO, $MgTiO_3$, $MgZrO_3$, $MgSrZrTiO_6$, Mg_2SiO_4, $CaSiO_3$, $MgAl_2O_4$, $CaTiO_3$, Al_2O_3, SiO_2, $BaSiO_3$ and $SrSiO_3$. These compositions can be BSTO and one of these components or two or more of these components in quantities from 0.25 weight percent to 80 weight percent with BSTO weight ratios of 99.75 weight percent to 20 weight percent.

The electronically tunable materials can also include at least one metal silicate phase. The metal silicates may include metals from Group 2A of the Periodic Table, i.e., Be, Mg, Ca, Sr, Ba and Ra, preferably Mg, Ca, Sr and Ba. Preferred metal silicates include Mg_2SiO_4, $CaSiO_3$, $BaSiO_3$ and $SrSiO_3$. In addition to Group 2A metals, the present metal silicates may include metals from Group 1A, i.e., Li, Na, K, Rb, Cs and Fr, preferably Li, Na and K. For example, such metal silicates may include sodium silicates such as Na_2SiO_3 and $NaSiO_3$-$5H_2O$, and lithium-containing silicates such as $LiAlSiO_4$, Li_2SiO_3 and Li_4SiO_4. Metals from Groups 3A, 4A and some transition metals of the Periodic Table may also be suitable constituents of the metal silicate phase. Additional metal silicates may include $Al_2Si_2O_7$, $ZrSiO_4$, $KalSi_3O_8$, $NaAlSi_3O_8$, $CaAl_2Si_2O_8$, $CaMgSi_2O_6$, $BaTiSi_3O_9$ and Zn_2SiO_4. The above tunable materials can be tuned at room temperature by controlling an electric field that is applied across the materials.

In addition to the electronically tunable dielectric phase, the electronically tunable materials can include at least two additional metal oxide phases. The additional metal oxides may include metals from Group 2A of the Periodic Table, i.e., Mg, Ca, Sr, Ba, Be and Ra, preferably Mg, Ca, Sr and Ba. The additional metal oxides may also include metals from Group 1A, i.e., Li, Na, K, Rb, Cs and Fr, preferably Li, Na and K. Metals from other Groups of the Periodic Table may also be suitable constituents of the metal oxide phases. For example, refractory metals such as Ti, V, Cr, Mn, Zr, Nb, Mo, Hf, Ta and W

may be used. Furthermore, metals such as Al, Si, Sn, Pb and Bi may be used. In addition, the metal oxide phases may comprise rare earth metals such as Sc, Y, La, Ce, Pr, Nd and the like.

The additional metal oxides may include, for example, zirconnates, silicates, titanates, aluminates, stannates, niobates, tantalates and rare earth oxides. Preferred additional metal oxides include Mg_2SiO_4, MgO, $CaTiO_3$, $MgZrSrTiO_6$, $MgTiO_3$, $MgAl_2O_4$, WO_3, $SnTiO_4$, $ZrTiO_4$, $CaSiO_3$, $CaSnO_3$, $CaWO_4$, $CaZrO_3$, $MgTa_2O_6$, $MgZrO_3$, MnO_2, PbO, Bi_2O_3 and La_2O_3. Particularly preferred additional metal oxides include Mg_2SiO_4, MgO, $CaTiO_3$, $MgZrSrTiO_6$, $MgTiO_3$, $MgAl_2O_4$, $MgTa_2O_6$ and $MgZrO_3$.

The additional metal oxide phases are typically present in total amounts of from about 1 to about 80 weight percent of the material, preferably from about 3 to about 65 weight percent, and more preferably from about 5 to about 60 weight percent. In one preferred embodiment, the additional metal oxides comprise from about 10 to about 50 total weight percent of the material. The individual amount of each additional metal oxide may be adjusted to provide the desired properties. Where two additional metal oxides are used, their weight ratios may vary, for example, from about 1:100 to about 100:1, typically from about 1:10 to about 10:1 or from about 1:5 to about 5:1. Although metal oxides in total amounts of from 1 to 80 weight percent are typically used, smaller additive amounts of from 0.01 to 1 weight percent may be used for some applications.

In one embodiment, the additional metal oxide phases may include at least two Mg-containing compounds. In addition to the multiple Mg-containing compounds, the material may optionally include Mg-free compounds, for example, oxides of metals selected from Si, Ca, Zr, Ti, Al and/or rare earths. In another embodiment, the additional metal oxide phases may include a single Mg-containing compound and at least one Mg-free compound, for example, oxides of metals selected from Si, Ca, Zr, Ti, Al and/or rare earths. The high Q tunable dielectric capacitor utilizes low loss tunable substrates or films.

To construct a tunable device, the tunable dielectric material can be deposited onto a low loss substrate. In some instances, such as where thin film devices are used, a buffer layer of tunable material, having the same composition as a main tunable layer, or having a different composition can be inserted between the substrate and the main tunable layer. The low loss dielectric substrate can include magnesium oxide (MgO), aluminum oxide (Al_2O_3), and lanthium oxide ($LaAl_2O_3$).

Compared to semiconductor varactor based tunable filters, the tunable dielectric capacitor based tunable filters of this invention have the merits of lower loss, higher power-handling, and higher IP3, especially at higher frequencies (>10GHz).

The present invention is a tunable combline filter, which is tuned by voltage-controlled tunable dielectric capacitors. The tunable filter includes a plurality of many coupled coaxial combline resonators operating in the microwave frequency range. In the filter structure, the tuning element is a voltage-controlled tunable dielectric capacitor. Since the tunable capacitors show high Q, high IP3 (low intermodulation distortion) and low cost, the tunable filter in the present invention has the advantage of low insertion loss, fast tuning, and high power handling.

While the present invention has been described in terms of its preferred embodiments, it will be apparent to those skilled in the art that various changes can be made to the disclosed embodiments without departing from the scope of the invention as set forth in the following claims.